The Gargasian (Middle Aptian) of La Marcouline section at Cassis-La Bédoule (SE France): Stable isotope record and orbital cyclicity

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Abstract: Bulk rock stable isotope analysis of La Marcouline section (Cassis-La Bédoule area, SE France) revealed a general trend of decreasing $\delta^{13}C$ and $\delta^{18}O$ values from the bottom to the top of the section. The decrease in $\delta^{13}C$ values reflects a global trend in Middle Aptian times, namely a return to pre-excursion values of $\delta^{13}C$ values following a major, positive excursion in the Early Aptian, which is a reflection of the Oceanic Anoxic Event (OAE) 1a.

Power spectra of the bedding rhythms suggest that precessional and long eccentricity cycles of the MILANKOVITCH band controlled the deposition of marl-limestone bundles. This can be interpreted as the result of a forcing by insolation at low latitudes which resulted in a monsoon-controlled precipitation pattern, that in turn induced the deposition of clay-rich beds. Conversely, limestone beds were formed in periods of dryer climate. Higher sea-surface productivity during wet periods may have been be caused by an increase in continental runoff and a consequent enhancement in the delivery of nutrients to epicontinental basins.

An orbital cyclicity in the sedimentary patterns in La Marcouline section provides the opportunity to calibrate the duration of the well-established *G. ferreolensis* foraminiferal Zone with that of orbital chronology. The *G. ferreolensis* Zone at Cassis-La Bédoule spans 33 precessional cycles and its duration is thus estimated to be approximately 760 ka. This length of time is significantly shorter than the estimates of published timescales for this zone and thus may be an argument for proposing that the Gargasian substage is significantly shorter than its currently accepted range.

Key Words: Middle Aptian; Gargasian; stable isotopes; planktonic foraminiferal biostratigraphy; orbitochronology

Résumé : ***Le Gargasien (Aptien moyen) de la coupe de La Marcouline à Cassis-La Bédoule (SE France) : enregistrement des isotopes stables et cyclicité orbitale.-*** Une analyse sur roche totale des isotopes stables de la coupe de la carrière de La Marcouline (secteur de Cassis-La Bédoule, SE de la France) a révélé une tendance générale à la décroissance des valeurs de $\delta^{13}C$ et $\delta^{18}O$ depuis la base jusqu'au sommet de la coupe. La décroissance des valeurs de $\delta^{13}C$ reflète une tendance globale durant l'Aptien moyen, à savoir un retour à des valeurs inférieures à celles de l'excursion positive observée à l'Aptien inférieur, qui correspond à l'événement anoxique océanique OAE1a.

L'analyse spectrale des rythmes de stratification suggère que les cycles de précession et les cycles longs d'excentricité de type MILANKOVITCH ont contrôlé le dépôt des couplets marne-calcaire. Ceci peut s'interpréter comme le résultat d'un forçage solaire aux basses latitudes qui a engendré un mode de précipitations contrôlé par la mousson, induisant le dépôt de couches riches en argile. A l'inverse, les niveaux calcaires se sont déposés durant les périodes de climat plus sec. La plus forte productivité des eaux de surface durant les périodes humides peut avoir été causée par un accroissement des apports venant du continent conduisant à une augmentation des éléments nutritifs au sein des bassins épicontinentaux.

La détection d'une cyclicité orbitale dans les rythmes sédimentaires de la coupe de La Marcouline fournit l'occasion de calibrer avec la chronologie orbitale la durée de la zone bien caractérisée par l'espèce de foraminifère planctonique *G. ferreolensis*. Dans le secteur de Cassis-La Bédoule cette zone s'étage sur 33 cycles précessionels et sa durée peut ainsi être estimée à environ 760.000 ans. Cet intervalle de temps est sensiblement plus bref que les estimations figurant dans certaines échelles de temps publiées jusqu'à présent pour ladite zone. Cette nouvelle donnée constitue donc un argument qui autorise à proposer, pour le sous-étage Gargasien, une durée plus brève que celle qui est admise jusqu'ici.

Mots-Clefs : Aptien moyen ; Gargasien ; isotopes stables ; biostratigraphie par foraminifères planctoniques ; orbitochronologie

Introduction

The Gargasian of the La Marcouline Quarry Section near the Cassis-La Bédoule railway station (SE France) offers a unique opportunity to correlate a precise planktonic foraminiferal zonation (MOULLADE *et alii*, 2005) to high-resolution stable oxygen and carbon isotope curves and to an orbital stratigraphy based on well expressed marl-limestone cyclicity. The

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sections in the Cassis-La Bédoule area are especially well suited to the determination of a high-resolution stratigraphy for the Early-Middle Aptian. Excellent outcrops in which the rate of sedimentation was relatively high and in conjunction with a long-continued, uninterrupted sedimentary pattern are favorable to such an in-depth examination and should enable us to solve some problems in stratigraphic correlation that still exist in spite of extensive study of key sections in Italy and in the Vocontian Basin SE France). In those localities sediments were deposited in deeper water with lower sedimentation rates and may contain hiatuses (MENEGATTI *et alii*, 1998; ERBA *et alii*, 1999; WISSLER *et alii*, 2002). In particular our understanding of the orbital forcing of the Cretaceous carbon isotope record and estimates of the duration of individual carbon isotope excursions may benefit greatly from direct correlation of carbon isotope and sedimentary cycles expressed in fluctuations of carbonate-clay ratios (*e.g.* KUHNT *et alii*, 2005; SAGEMAN *et alii*, 2006, for the Cenomanian-Turonian isotope excursion).

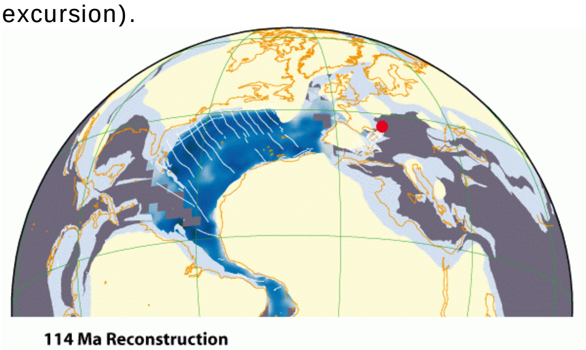

Figure 1: Middle-Late Aptian (114 Ma) paleo-geographic reconstruction based on the finite rotation dataset published by HAY *et alii* (1999) and available on the ODSN website (http://www.odsn.de/odsn/services/paleomap/paleomap.html).
The sketched shoreline was taken from SMITH *et alii* (1994). Position of the La Marcouline Section is indicated by red dot within a NW Tethys marginal basin.

The studied section is situated close to the European continental block (Fig. 1), namely in the South Provencal Basin, which is located within the Provence carbonate platform and is not far from the adjacent Vocontian Basin (see MOULLADE *et alii*, 2004; MOULLADE & TRONCHETTI, 2004, for more details on the geographic location and geological setting). These are key areas for understanding the relationships between Cretaceous climate, nutrient fluxes, productivity and carbon fluxes from the continent or the carbonate platforms to the open ocean (BRÉHÉRET, 1997; WEISSERT *et alii*, 1998; WISSLER *et alii*, 2003). Moreover, the section is located in an area of potentially high sensitivity to variability in precessional insolation in the Cretaceous like that of the U.S. Western Interior Seaway and that of the archipelago along the northwestern margin of the Tethys (Fig. 1) (FLOEGEL, 2001).

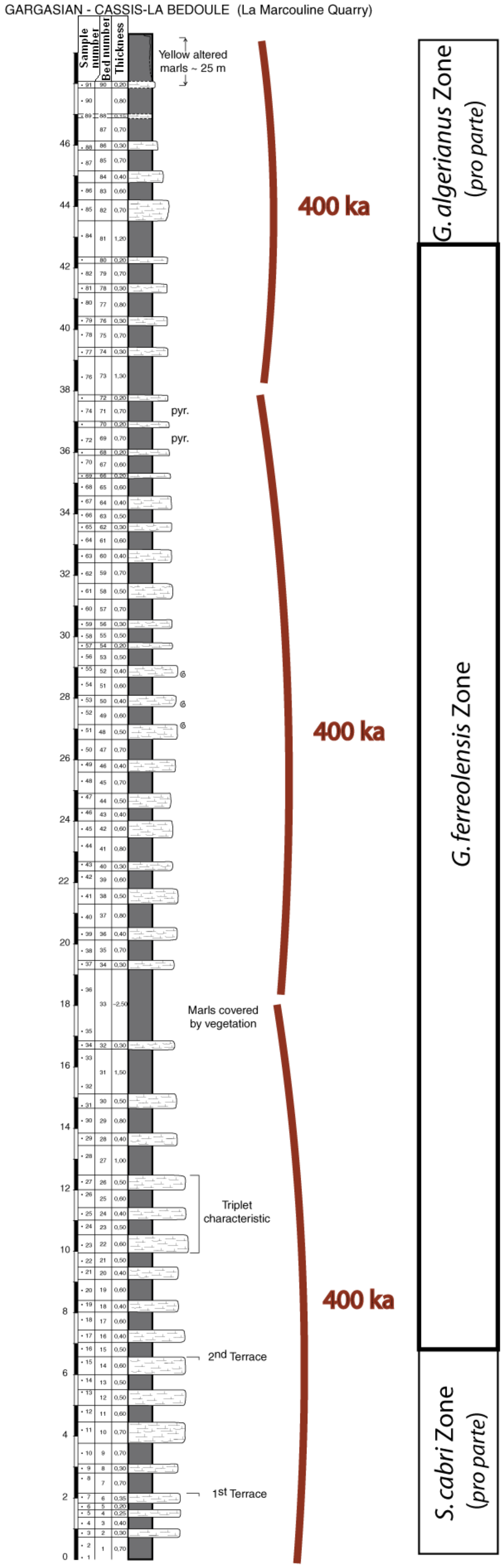

Figure 2: Log of the La Marcouline Quarry Section with sample positions and bed thicknesses used for spectral analyses. The main 400 ka long eccentricity cycles and the boundaries of planktonic foraminiferal zones are indicated.

Here we present a first bed-resolution carbon isotope stratigraphy and cyclostratigraphy of the Gargasian at La Marcouline, which is integrated with previously published biostratigraphic and chemostratigraphic records (MOULLADE *et alii*, 2004, 2005), to investigate the potential of this section for future, millennial-scale studies of Aptian climate variability and orbital forcing.

Material and methods

We sampled the lower and middle Gargasian beds of the La Marcouline Quarry section near the Cassis-La Bédoule railway station (Fig. 2). The lowermost Gargasian could not be properly sampled in this section, for an interval of approximately 5 m, straddling the Bedoulian-Gargasian transition, is there covered by a road and by vegetation (MOULLADE *et alii*, 2004). The upper part of the Gargasian is missing, due to pre-Cenomanian erosion that affected the entire area.

A total of 91 bulk-rock samples from the light grey micritic limestones and grey clay-rich marlstones of La Marcouline section have been analyzed for stable oxygen and carbon isotopes. The relative positions of samples in the composite section according to bed numbers and thickness in meters are given in Figure 2. Sampled lithologies include homogeneous micritic limestones (nanno-ooze) apparently without significant amounts of late diagenetic cementation, marly limestones and marls (BELTRAN *et alii*, 2007). Samples taken from freshly cut rock slabs were crushed and carefully homogenized in an agate mortar. Isotopic measurements were made with a Finnigan MAT 251 mass spectrometer installed at the Leibniz-Labor für Altersbestimmung und Isotopenforschung in Kiel. The instrument is coupled on-line to a Carbo-Kiel device for automated CO_2 preparation from carbonate samples for isotopic analysis. CO_2 was generated by the addition of orthophosphoric acid to each sample. Measurements have an accuracy of ± 0.057 ‰ for carbon and ± 0.084 ‰ for oxygen isotopes. The results were calibrated using the National Institute Bureau of Standards and Technology (Gaithersburg, Maryland), carbonate isotope standard NBS 20 and, in addition, NBS 19 and 18 and are reported on the Vienna PeeDee belemnite (VPDB) scale.

Spectral analyses were made using field measurements of the section. The sediments were classified into four different lithologies (limestones, marly limestones, calcareous marlstones, and marlstones). These lithologies correspond well with grey values derived from photographs of the outcrops. Grey scale values were obtained from scanned color photographs, taken in the late afternoon, when light conditions permitted shadow-free images of the outcrop surface. Grey scale curves were generated for well-exposed parts of the section using NIH Image software (Fig. 3). Input data for spectral analysis were based on (1) the thickness of strata measured in the outcrop and (2) a classification by the quantity of carbonate in individual samples grouped into four classes

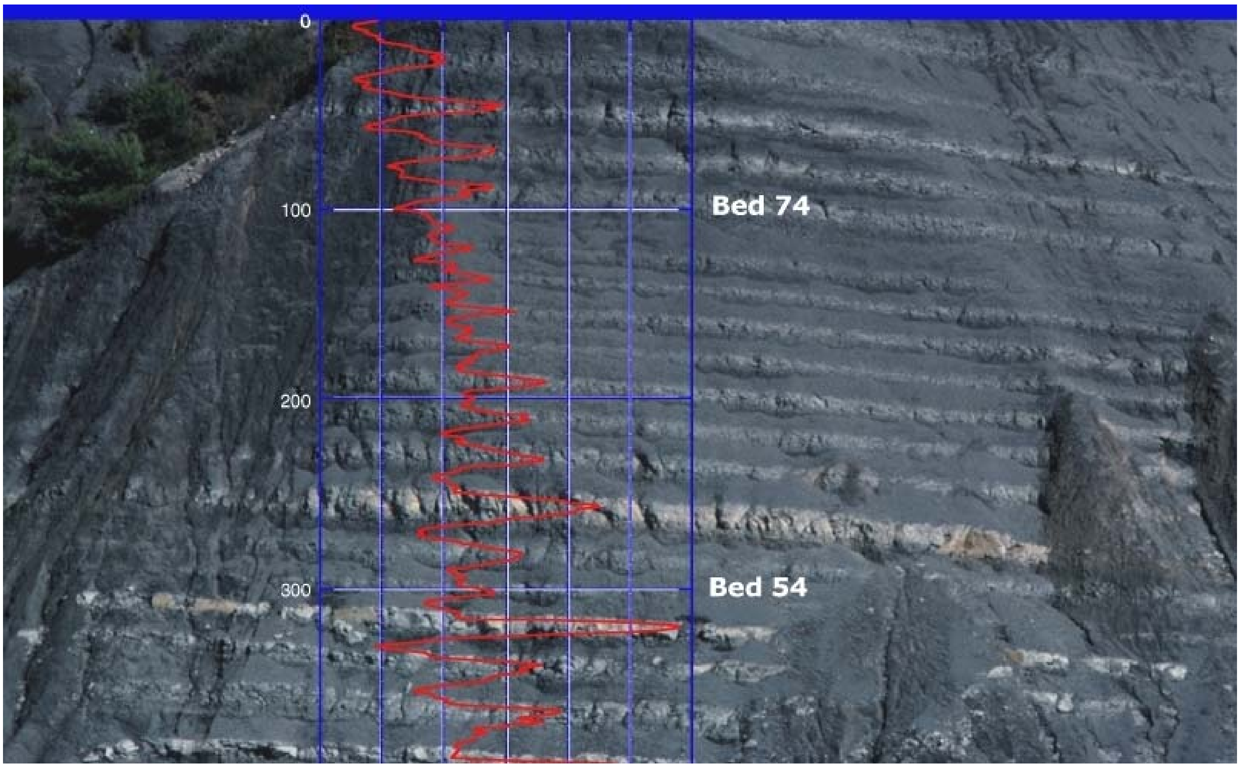

Figure 3: Outcrop photograph overlain by greyscale values generated by NIH Image analysis of digitalized color slides.

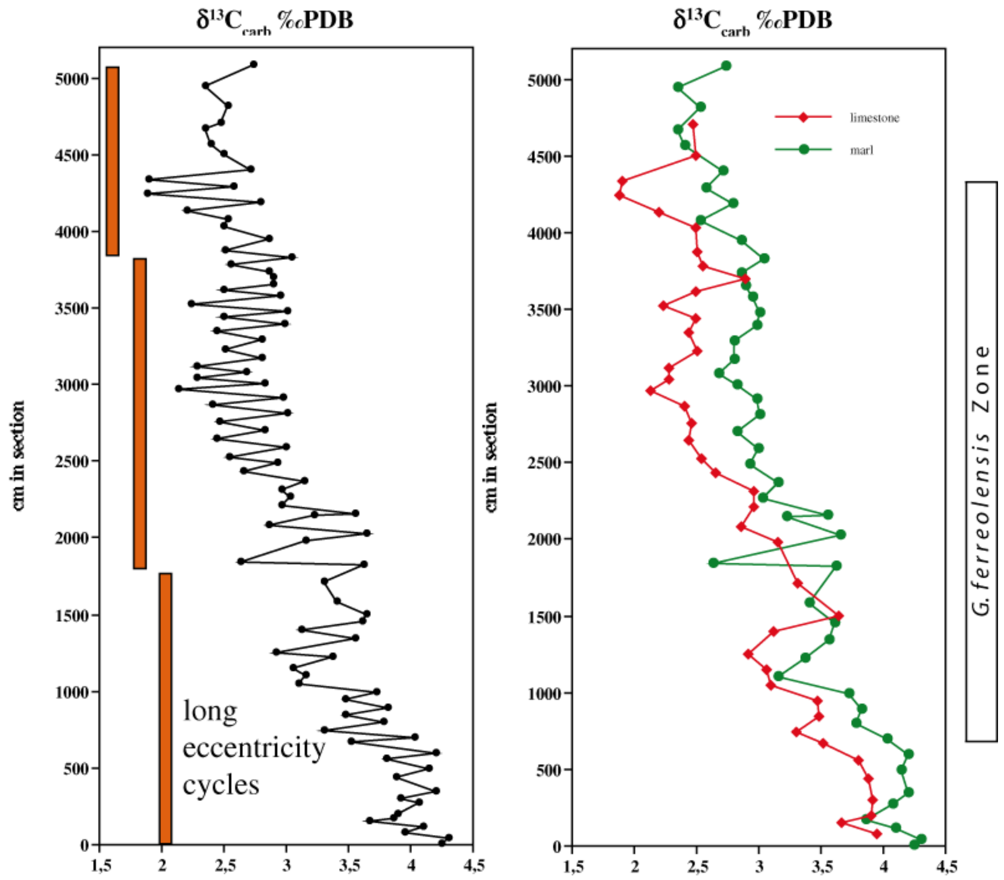

Figure 4: Carbonate carbon isotope curve of the La Marcouline section.

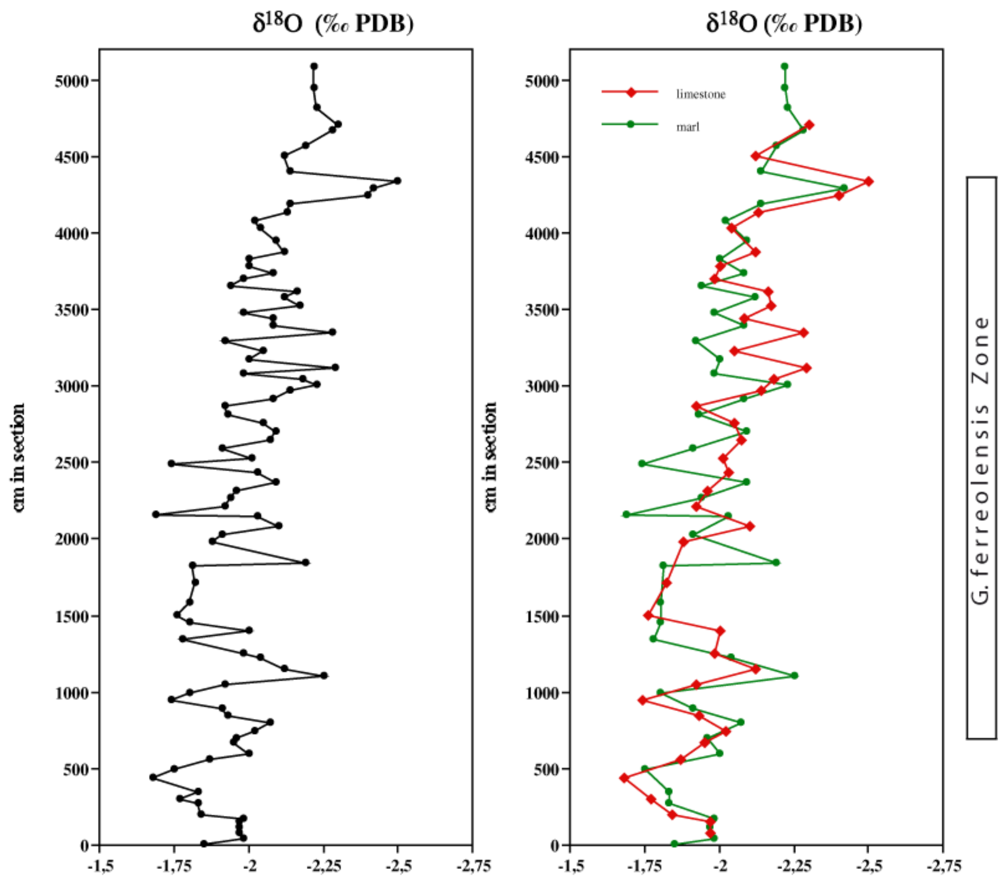

Figure 5: Carbonate oxygen isotope curve of the La Marcouline section.

based on the carbonate values of individual samples as related to the grey-scale value of the sediment. BLACKMAN-TUKEY power spectra were generated from marl limestone bedding rhythms and carbonate content estimations using Analyserie 1.2 (PAILLARD *et alii*, 1996).

Results

Carbon isotope stratigraphy

Bulk rock stable isotope analysis of the la Marcouline section revealed a general trend of decreasing $\delta^{13}C$ values from more than 4 ‰ at the bottom to approximately 2.5 ‰ at the top of the section (Fig. 4). This trend is paralleled by a decrease in $\delta^{18}O$ values, that probably indicates either a warming trend or a freshening of surface waters (Fig. 5). The decrease in $\delta^{13}C$ values reflects the Middle Aptian return to pre-excursion values after the major positive excursion in the Early Aptian, which reflects the Oceanic Anoxic Event (OAE) 1a (Fig. 6) (KUHNT *et alii*, 1998; MOULLADE *et alii*, 1998). From approximately 30 m to 50 m the $\delta^{13}C$ values stay almost constant at 2.2-2.5 ‰ for limestone and 2.5-2.8 ‰ for marls. This interval probably corresponds to a $\delta^{13}C$ plateau with values of approximately 2.2 ‰ $\delta^{13}C$ in the upper part of the *G. ferreolensis* Zone observed in previous studies in the Vocontian Basin (HERRLE *et alii*, 2004; FÖLLMI *et alii*, 2006) (Fig. 6). The second decrease in $\delta^{13}C$, that culminates in minimum values between 1.0 and 1.5 ‰ in the Niveau Fallot of the Vocontian sections, is not recorded in La Marcouline section, for this event starts significantly above the FO of *G. algerianus* and only the first five meters of the *G. algerianus* Zone crop out in La Marcouline section.

Marl and limestone layers differ significantly in $\delta^{13}C$ values (Fig. 4). Generally, the $\delta^{13}C$ values of limestones are approximately 0.5 ‰ lower than those of marls. This difference might be explained by an early diagenetic cementation of limestones, causing pore water with a lower $\delta^{13}C$ value to have a greater effect on the limestone deposits. However, there is no significant difference in the $\delta^{18}O$ values of marls and limestones (Fig. 5); this suggests that the differences in carbon isotopes are a primary signal and are not caused by cementation on the sea floor or during burial. A better explanation for the observed difference in the $\delta^{13}C$ values of limestone and marl may involve an increase in sea surface productivity triggered by an enhanced nutrient input caused by a more important continental runoff during the deposition of clay. This might have caused the "biological pump" to be more active during periods of clay sedimentation.

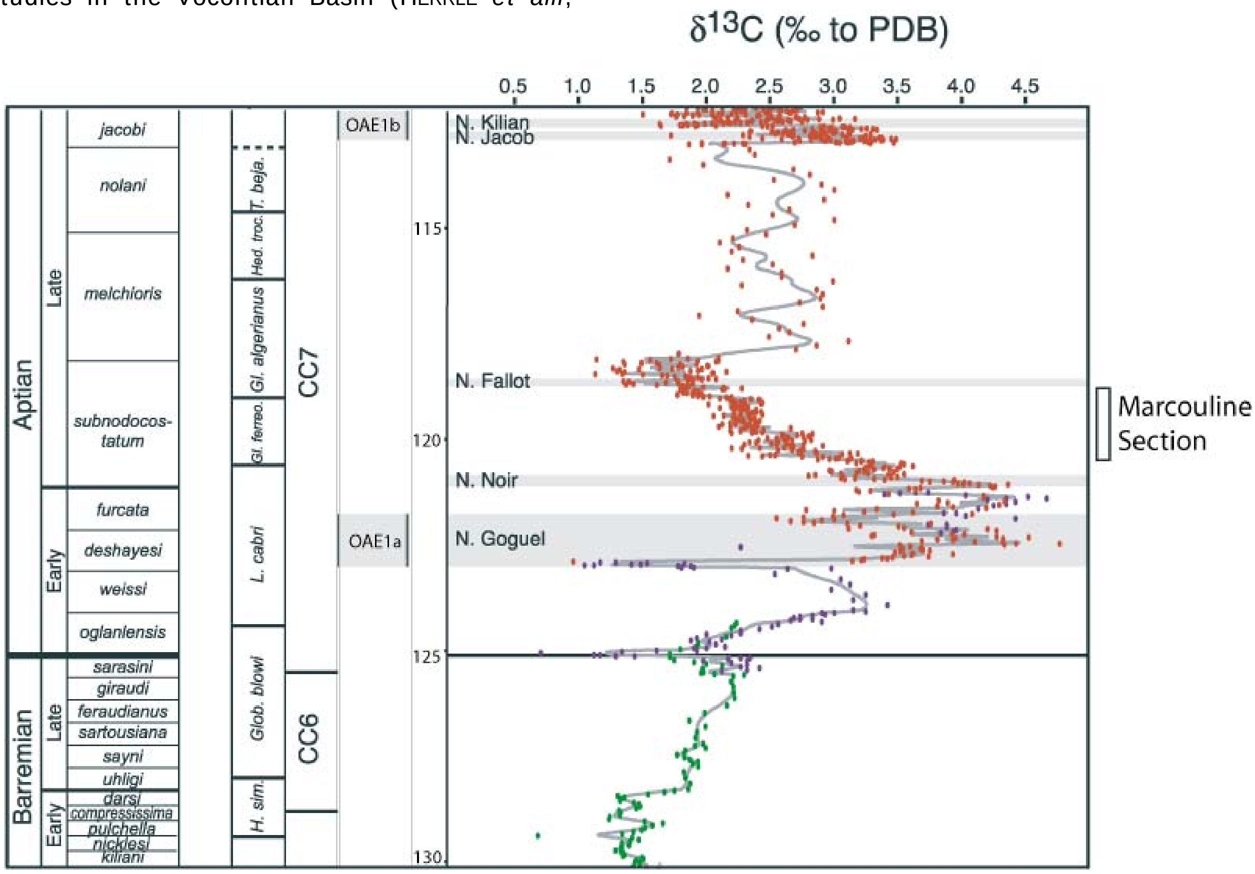

Figure 6: Composite carbonate carbon isotope curve of the Vocontian realm and the Cassis-La Bédoule area, modified after FÖLLMI *et alii* (2006). Data represented by green dots are from GODET *et alii* (2006), data in blue are from KUHNT *et alii* (1998), and data in red are from HERRLE *et alii* (2004). Timescale is according to OGG *et alii* (2004).

Time series analyses

BLACKMAN-TUKEY power spectra of the marl-limestone rhythms exhibit significant peaks at a frequency of 0.01 cycles/cm (wavelength of approximately 1 m) and 0.0005 cycles/cm (wavelength of 20 m) (Fig. 7). The high frequency cycles coincide with the apparent marl / limestone couplets and may be explained by precessional cycles controlling the intensity of precipitation and continental runoff (COTILLON & RIO, 1984; FLOEGEL, 2001; FLOEGEL & WAGNER, 2006). The low frequency cycles apparently correspond to the 400 ka long eccentricity cycles that modulate the precession (Fig. 8). The absence of 100 ka short eccentricity "bundles", a common feature in other lower Cretaceous marl-limestone cycles (*e.g.* in the Piobbico core, FISCHER *et alii*, 1991) is somewhat surprising. A possible explanation could be an orbital configuration with a normal amplitude of the long (400 ka) eccentricity cycle, but a low amplitude of the short (100 ka) eccentricity cycle. Such a configuration can last over two long eccentricity cycles and normally occurs every 2.4 Ma (LASKAR *et alii*, 2004). However, the orbital solution of LASKAR *et alii* (2004) goes back only 100 Ma, and the possibility of a node in the 100 ka periodicity of the earth's eccentricity in the Gargasian can be verified only when an orbital solution extending back to 120 Ma becomes available.

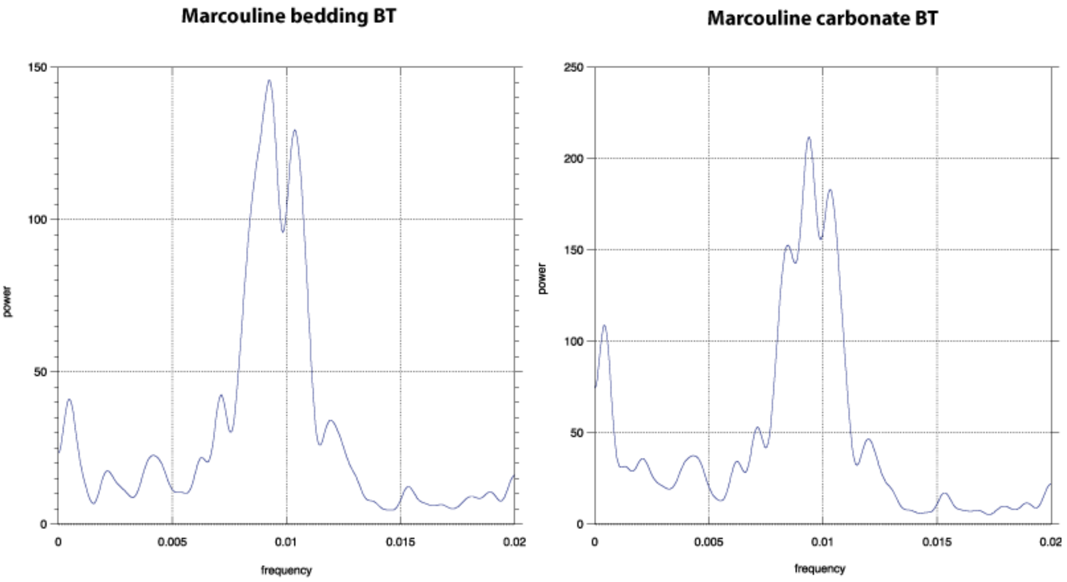

Figure 7: BLACKMAN-TUKEY power spectra of bedding rhythm (left graph) and carbonate content measurements (right graph). Band width = 0.001013, 0.625180 < ΔP (80.000000 %) / P < 2.057926.

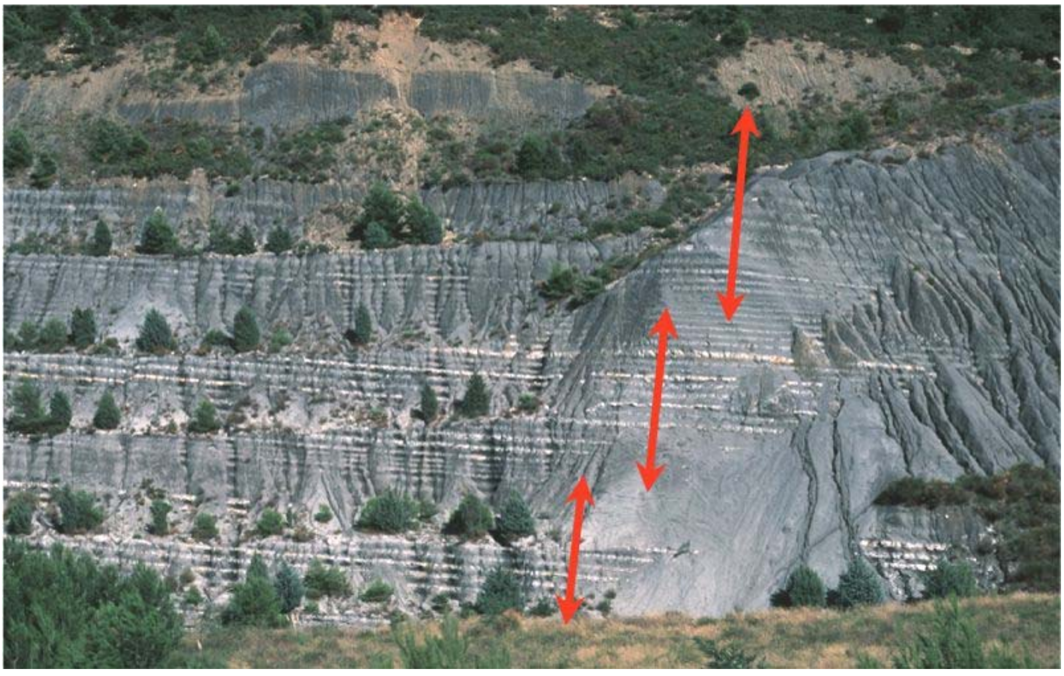

Figure 8: Outcrop photograph of the La Marcouline Quarry Section. The main 400 ka long eccentricity cycles are indicated.

Discussion

Orbital calibration of the duration of the *G. ferreolensis* Zone

The *G. ferreolensis* Zone in La Marcouline section is comprised between the last occurence of *Schackoina cabri*, observed in bed 15 at 6 m, and the first occurrence of *G. algerianus*, in bed 84 (43.05 m). Our results show that the duration of the *G. ferreolensis* Zone is approximately 33 precessional cycles (760 ka) or slightly less than two long eccentricity (400 ka) cycles (Figs. 1 & 8). The two foraminiferal bio-events mentioned above are dated 120.7 Ma and 119.0 Ma, respectively, in the Ogg *et alii* (2004) timescale, that is 1.7 Ma for the *G. ferreolensis* Zone. Thus, based on our work (< *circa* 0.8 Ma) the duration of the *G. ferreolensis* Zone appears to be significantly shorter than the 1.7 Ma reported in the Ogg *et alii* (2004) timescale.

The dominant frequency in Blackman-Tukey power spectra of carbonate and bedding is 0.01 cycles/cm; this corresponds to a wavelength of approximately 100 cm, which results in a sedimentation rate of *circa* 4.3 cm/ka, significantly higher than the sedimentation rate calculated from the Ogg *et alii* (2004) timescale (2.2 cm/ka, 37 m corresponding to 1.7 Ma). Using that scale, the duration of the main cycle in La Marcouline section would be 45 ka. However, the duration of the Aptian stage and its substages is controversial. Recent estimates of the length of the Aptian, made by combining radiometric (K-Ar ages of glauconite) and orbital chronology, suggest a duration of only 6.8 ± 0.4 Ma (Fiet *et alii*, 2006), *i.e.* half of that suggested by Ogg *et alii* (2004) (13.0 ± 2.0 Ma) (Table 1). The use of the recent time scale of (Fiet *et alii*, 2006) leads to the calculation of the length of the dominant period of La Marcouline section as 23 ka (in agreement with orbital precession) rather than 45 ka.

Base of Gargasian:	Ogg *et alii*, 2004: **121 Ma**
	Fiet *et alii*, 2006: **112.3 ± 0.4 Ma**
Top of Gargasian:	Ogg *et alii*, 2004: **115 Ma**
	Fiet *et alii*, 2006: **109.2 ± 0.4 Ma**
Duration of Gargasian:	Ogg *et alii*, 2004: **6 Ma**
	Fiet *et alii*, 2006: **3.1 Ma**

Table 1: Age estimates of the base, top and duration of the Gargasian substage after Ogg *et alii* (2004) and Fiet *et alii* (2006).

Conclusion

The La Marcouline section, located in the Lower Aptian historical stratotype area, provides an unusual opportunity to calibrate the duration of a well-established Gargasian foraminiferal biozone with orbital chronology. The *G. ferreolensis* Zone spans 33 precessional cycles and its duration can thus be calculated as approximately 760 ka. This length is significantly shorter than the estimate for this zone by Ogg *et alii* (2004), and may be an argument in favour of a significantly shorter Aptian stage as recently proposed by Fiet *et alii* (2006).

The carbon isotope stratigraphy of the lower Gargasian at La Marcouline is very similar to its records in the Vocontian trough (Herrle *et alii*, 2004; Föllmi *et alii*, 2006). This underlines the importance of carbon isotope stratigraphy for regional and global correlation of stratigraphic successions.

Acknowledgments

Isotope analyses were performed at the Leibniz-Labor für Altersbestimmung und Isotopenforschung at Kiel University by Helmut Erlenkeuser and his group. We thank Jean-Pierre Bellier and Maurice Renard for the joint field work at La Marcouline quarry and Brigitte Salomon (Kiel) for sample processing. We thank also two reviewers, Karl Föllmi and Emmanuela Mattioli, who provided helpful comments that improved the manuscript, as well as Nestor Sander for corrections of syntax and word choice that improved the readability of the text.

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